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LOW-MASS e^+e^- PAIRS FROM IN-MEDIUM ρ MESON PROPAGATION

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Abstract

Based on a realistic model for the rho meson in free space we investigate it's medium modifications in a hot hadron gas generated by hadronic rescattering processes, *i.e.* renormalization of intermediate two-pion states as well as direct rho meson scattering off hadrons. Within the vector dominance model the resulting in-medium rho spectral function is applied to calculate e^+e^- spectra as recently measured in heavy-ion collisions at CERN-SpS energies in the CERES experiment.

1 Introduction

The main goal of ultrarelativistic heavy-ion collisions is the identification of possible phase transitions in strongly interacting matter associated with chiral symmetry restoration and/or deconfinement. Experimental signatures of such transitions have to be disentangled from hadronic rescattering processes occurring in the later stages of central collisions.

Even though electromagnetic probes (photons and dileptons) can traverse the hadronic interaction zone without further distortion, the eventually observed spectra will be contaminated with contributions arising from conventional hadronic mechanisms and even decays after the hadronic freezeout. Focussing on the dilepton production, various 'conventional' background radiation, depending on the invariant mass range, is to be expected: for $M_{l^+l^-} \geq$1.5 GeV (l=μ, e) Drell-Yan processes have to be disentangled from, *e.g.*, a possible enhancement due to thermal $q\bar{q}$ annihilation in a QGP, or from anomalous J/Ψ, Ψ' suppression, which may or may not be due to a QGP formation; for $M_{l^+l^-} \leq$1.5 GeV, the spectrum should be dominated by hadron decays. Here,

the light vector mesons $\rho(770)$, $\omega(782)$ and $\phi(1020)$ are of particular interest, since they can directly couple to dilepton pairs. Among these the rho meson is of special importance due to it's short lifetime (τ_ρ^{free}=1.3 fm/c), which is about an order of magnitude smaller than the typical lifetime of the hadronic fireball, $\tau_{fireball}\approx$10 fm/c (to be compared with τ_ω^{free}=23 fm/c and τ_ϕ^{free}=44 fm/c).
A systematic study of low-mass e^+e^- production in p-Be, p-Au and S-Au collisions at CERN-SpS energies has recently been performed by the CERES/NA45 collaboration [1]. Whereas their event generator (accounting for 'primary' hadron decays) can succesfully describe the p-A data, an overall factor of about 5 enhancement was observed in the S-Au case, reaching a maximum factor of $\sim$10 around invariant masses $M_{e^+e^-}\simeq$0.4 GeV (similar results have been obtained by the HELIOS-3 collaboration [2]; preliminary data from Pb-Au collisions further confirm these findings [3]). The inclusion of free $\pi^+\pi^- \to e^+e^-$ annihilation in transport [4, 5] or hydrodynamical [6, 7] simulations of the collision dynamics has been shown to reduce this discrepancy, still leaving a factor of up to 3 too little yield below the ρ mass. So far, the only *quantitative* explanation of these data could be achieved by assuming a density and temperature dependent dropping ρ mass according to the Brown-Rho scaling conjecture [8], interpreted as a signature of (partial) chiral symmetry restoration. However, in this contribution we try to demonstrate that 'conventional' hadronic rescattering mechanisms of the ρ meson in a hot and dense hadronic enviroment seem to be sufficient to account for the experimentally observed e^+e^- excess in central S-Au (200 GeV/u) and Pb-Au (158 GeV/u) collisions [9].

2 The Free ρ Meson and Modifications in a Hot Hadron Gas

2.1 The ρ Meson in Free Space

A satisfactory yet simple description of the ρ meson in the vacuum can be achieved by renormalizing a 'bare' ρ of mass m_ρ^{bare} through coupling to intermediate two-pion states. The scalar part of the free ρ propagator then reads

$$D_\rho^0(M) = [M^2 - (m_\rho^{bare})^2 - \Sigma^0_{\rho\pi\pi}(M)]^{-1} \ , \tag{1}$$

where the selfenergy

$$\begin{aligned} \Sigma^0_{\rho\pi\pi}(M) &= \bar\Sigma^0_{\rho\pi\pi}(M) - \bar\Sigma^0_{\rho\pi\pi}(0) \ , \\ \bar\Sigma^0_{\rho\pi\pi}(M) &= \int \frac{k^2 dk}{(2\pi)^2} \ v_{\rho\pi\pi}(k)^2 \ G^0_{\pi\pi}(M,k) \ , \end{aligned} \tag{2}$$

contains the $\rho\pi\pi$ vertex function $v_{\rho\pi\pi}$ as well as the free two-pion propagator $G^0_{\pi\pi}(M,k)$. The subtraction at zero energy ensures the correct normalization of the pion electromagnetic form factor ($F_\pi(0)$=1), which in the vector dominance model (VDM) is given by

$$|F^0_\pi(M)|^2 = (m_\rho^{bare})^4 \; |D^0_\rho(M)|^2 \; . \tag{3}$$

The bare mass m_ρ^{bare} and coupling $g_{\rho\pi\pi}$ (entering $v_{\rho\pi\pi}$) are easily tuned to reproduce the experimental data on p-wave $\pi\pi$ scattering and the pion electromagnetic form factor in the timelike region [9, 10].

2.2 Medium Modifications in $\pi\pi$ Propagation

The most important medium effects in the intermediate two-pion states of the ρ propagator are attributed to interactions with surrounding baryons, as discussed in refs. [11, 12, 13] for the case of cold nuclear matter. Therefore one first needs a realistic model for the in-medium single-pion propagator D_π. As is well known from pion nuclear phenomenology, pion-induced p-wave nucleon-nucleonhole (NN^{-1}) and delta-nucleonhole (ΔN^{-1}) excitations are the dominant mechanism. Since we are interested in URHIC's at CERN-SpS energies (160-200 GeV/u), thermal excitations of the system should be taken into account, which, in the baryonic sector, are dominated by a large $\Delta(1232)$ component. Thus we extend the particle-hole picture to include π-Δ interactions as well in form of $N\Delta^{-1}$ and $\Delta\Delta^{-1}$ excitations.
To calculate the corresponding medium modified ρ selfenergy, vertex corrections of the $\pi\pi\rho$ vertex have to be included to ensure the conservation of the vector current. We here employ the approach of Chanfray and Schuck [13]. Within a full off-shell treatment of the pion propagation in connection with the afore mentioned extension to finite temperature the imaginary part of the in-medium ρ selfenergy at zero 3-momentum can be cast in the form [10]

$$\begin{aligned} \mathrm{Im}\Sigma_{\rho\pi\pi}(q_0,\vec{0}) = & -\int\limits_0^\infty \frac{k^2\;dk}{(2\pi)^2}\; v_{\rho\pi\pi}(k)^2 \int\limits_0^{q_0} \frac{dk_0}{\pi}\;[1+f^\pi(k_0)+f^\pi(q_0-k_0)] \\ & *\;\; \mathrm{Im}D_\pi(q_0-k_0,k)\;\mathrm{Im}\{\alpha(q_0,k_0,k)D_\pi(k_0,k)+\frac{\Pi_L(k_0,k)}{2k^2}+\frac{\Pi_T(k_0,k)}{k^2}\} \end{aligned} \tag{4}$$

with the longitudinal and transverse spin-isospin response functions $\Pi_L(k_0,k)$ and $\Pi_T(k_0,k)$, a factor α characterizing vertex corrections and thermal Bose distributions f^π. The real part is obtained from a dispersion integral:

$$\mathrm{Re}\Sigma_{\rho\pi\pi}(q_0) = -\mathcal{P}\int\limits_0^\infty \frac{dE'^2}{\pi}\frac{\mathrm{Im}\Sigma_{\rho\pi\pi}(E')}{q_0^2-E'^2}\frac{q_0^2}{E'^2}\;. \tag{5}$$

2.3 Rho-Nucleon and Rho-Delta Interactions

In analogy to the pionic interactions with the surrounding medium direct interactions of the (bare) rho meson with nucleons and deltas may have a substantial impact. Based on the observation that certain baryonic excitations (especially $N(1720)$ and $\Delta(1905)$) exhibit a strong coupling to the ρN decay channel (which suggests to identify them as 'ρN resonances'), Friman and Pirner proposed to derive a corresponding in-medium ρ selfenergy. As for pions, this is conveniently done in terms of p-wave (ρ-like) particle-hole excitations [14]. The $\rho N(1720)N$ and $\rho\Delta(1905)N$ coupling constants are fixed by the experimental branching ratios (where it is very important to account for the finite ρ-width in free space to obtain realistic values). Within our off-shell treatment we are also able to incorporate lower lying ρN and $\rho\Delta$ contributions, the coupling constants for which are taken from the Bonn potential. Thus we obtain

$$\Sigma_{\rho B}(q_0,q) = -q^2 \sum_\alpha \chi_{\rho\alpha}(q_0,q) \tag{6}$$

where the summation is over $\alpha = NN^{-1}, \Delta N^{-1}, N\Delta^{-1}, \Delta\Delta^{-1}, N(1720)N^{-1}$, $\Delta(1905)N^{-1}$, and the susceptibilties $\chi_{\rho\alpha}$ contain the loop integrals of the corresponding particle-hole bubble as well as short-range correlation corrections (parametrized by Migdal paprameters g') [9]. In fig. 1 we display the transverse part of the ρ spectral function,

$$\mathrm{Im}D_\rho^T(M,q) = \mathrm{Im}\left(\frac{1}{M^2-(m_\rho^{bare})^2-\Sigma^0_{\rho\pi\pi}(M)-\Sigma_{\rho B}(q_0,q)}\right) , \tag{7}$$

at normal nuclear matter density and small temperature T=5 MeV with no medium modifications applied to the two-pion states. A pronounced structure of various branches is observed, in particular the $\rho N(1720)N^{-1}$, which may be phrased 'Rhosobar' (in analogy to the 'Pisobar' $\pi\Delta N^{-1}$).

2.4 Rho-Pion and Rho-(Anti)Kaon Interactions

Since in URHIC's at CERN-SpS energies large numbers of secondaries are produced, we furthermore evaluate ρ scattering off the most abundant surrounding mesons, i.e. pions and (anti-) kaons. Assuming the interactions to be dominated by $a_1(1260)$ and $K_1/\bar{K}_1(1270)$ formation, the corresponding ρ selfenergy (in the Matsubara approach) can be written as

$$\Sigma_{\rho M}(q_0,\vec{q}) = \int \frac{d^3p}{(2\pi)^3}\frac{1}{2\omega_p^M}[f^M(\omega_p^M)-f^{\rho M}(\omega_p^M+q_0)]\ M_{\rho M}(p_M,q) \tag{8}$$

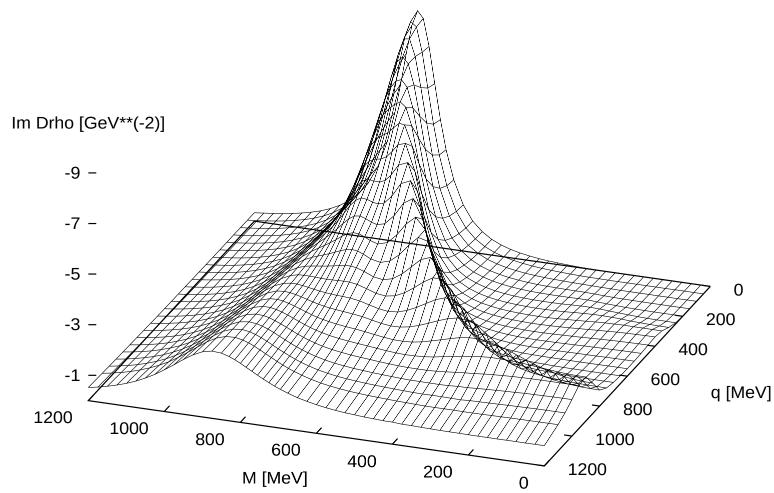

Figure 1: Imaginary part of the ρ propagator in cold nuclear matter at a density ρ=ρ_0 when including 'Rhosobar-like' ρN interactions.

(M=π, K, $\bar{K}$). The invariant scattering amplitude $M_{\rho M}$ is derived from a suitable (gauge invariant) lagrangian [15].
As long as the meson chemical potentials are kept zero the effect of ρ-M scattering is rather small: at highest temperatures considered (T=170 MeV) we find a ~60 MeV broadening of the ρ spectral function [9], which is similar to the results of ref. [16].

3 e^+e^- Spectra from in-Medium $\pi^+\pi^-$ Annihilation at the CERN-SpS

Invoking the phenomenologically well established VDM the dilepton prodcution rate from $\pi^+\pi^-$ annihilation can be expressed in terms of the ρ spectral function as

$$\frac{dN_{\pi^+\pi^-\to e^+e^-}}{d^4x d^4q} = -\frac{\alpha^2 (m_\rho^{bare})^4}{\pi^3 g_{\rho\pi\pi}^2} \; \frac{f^\rho(q_0;T)}{M^2} \; \mathrm{Im} D_\rho(q_0,q;\mu_B,T) \qquad (9)$$

with

$$\mathrm{Im}D_\rho = \frac{1}{3}\left(\frac{\mathrm{Im}\Sigma_\rho^L}{|M^2-(m_\rho^{bare})^2-\Sigma_\rho^L|^2}+\frac{2\mathrm{Im}\Sigma_\rho^T}{|M^2-(m_\rho^{bare})^2-\Sigma_\rho^T|^2}\right) \tag{10}$$

The full in-medium ρ selfenergy Σ_ρ is the sum of the contributions discussed in sects. 2.2-2.4 (decomposed in transverse and longitudinal parts) [9]. Fig. 2 shows the ρ spectral function at fixed chemical potentials and given three-momentum: with increasing temperature/density a dramatic broadening is found, which, in particular, results in a pronounced enhancement over the free curve for invariant masses below $M\simeq 0.6$ GeV.

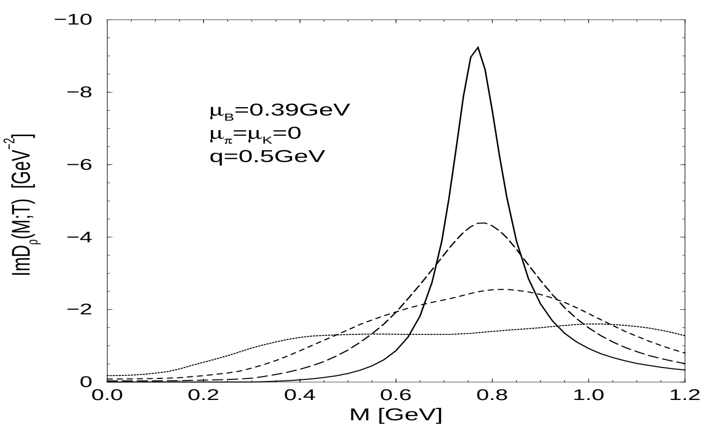

Figure 2: Imaginary part of the ρ propagator in a hot hadron gas at temperatures T=127 MeV (long-dashed curve), T=149 MeV (dashed curve) and T=170 MeV (dotted curve) as well as in vacuum (full curve).

For calculating e^+e^- invariant mass spectra as measured in the CERES experiment the differential rate eq. (9) has to be integrated over 3-momentum and the space-time history of a central 200 GeV/u S-Au reaction. For that we assume a temperature/density evolution as found in recent transport calculations [5]. The experimental acceptance cuts on the dilepton tracks as well as the finite mass resolution of the CERES detector are also included. We supplement our results for $\pi^+\pi^-$ annihilation with contributions from free Dalitz decays (π_0,$\eta \to \gamma e^+e^-$, $\omega \to \pi^0 e^+e^-$) and free $\omega \to e^+e^-$ decays as extracted from ref. [5], where medium effects are expected to be of minor importance. As can be seen from the fig. 3, the use of the in-medium ρ propagator (full curve) leads to reasonable agreement with the experimental e^+e^- spectrum as

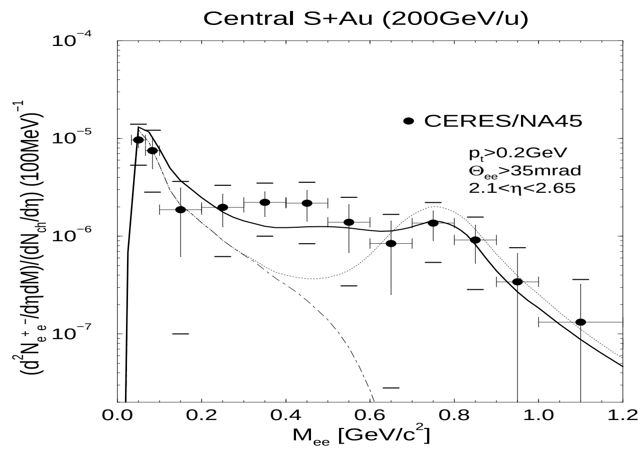

Figure 3: Dilepton spectra in central S+Au collisions from free Dalitz decays (dashed-dotted line), free Dalitz+ω+ρ (dotted line) and free Dalitz+ω + in-medium ρ decays (full line).

observed in central S+Au collisions at 200 GeV/u. The same is true when comparing to the preliminary data for the heavier Pb+Au system at 158 GeV/u (see fig. 4), where an accordingly modified temperature/density evolution has been employed.

To summarize, our findings seem to indicate that hadronic rescattering processes in in-medium ρ propagation seem to resolve the discrepancy between the experimentally observed e^+e^- enhancement at CERN-SpS energies

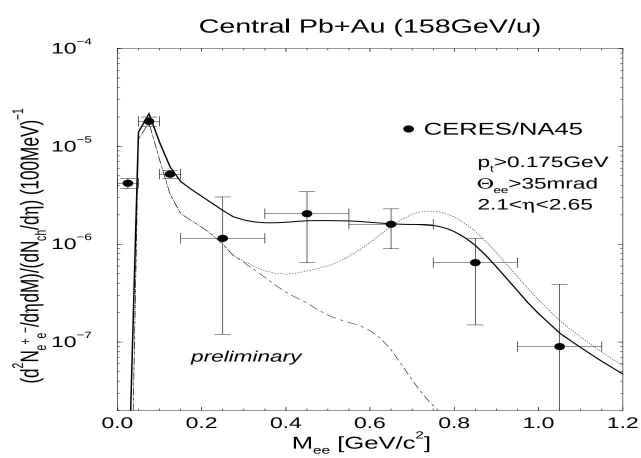

Figure 4: Same as fig. 3, but for central Pb+Au collisions.

and theoretical results based on free $\pi^+\pi^-$ annihilation. Even though further improvements to our analysis need to be done, we tend to conclude that the BR-scaling conjecture of a dropping ρ mass is presumably not an independent phenomenon. For disentangling such a uniform mass shift from the dynamic mechanisms we discussed, the measurement of invariant mass spectra in various p_T bins might provide new insights.

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